Cover Page

Title of the Grant: "Intent of Study on the Use of a Dual Airborne Laser Scanner (ALS) in Conjunction with a Tactical Grade Inertial Measurement Unit (IMU) for Unmanned Aerial Vehicle (UAV) Navigation and Mapping in Unknown, Non-Global Positioning System (GPS), Environments"

Type of Report: Final

Name of the PI: Dr. Maarten Uijt de Haag

Period covered: 30 September 2005 – 30 March 2006

Name of the recipient: Ohio University
105 Research and Technology Center
Athens, OH 45701

Grant number: FA9550-05-1-0495

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
05-08-2006

2. REPORT TYPE
FINAL

3. DATES COVERED *(From - To)*
30-09-2005 – 30-03-2006

4. TITLE AND SUBTITLE
"Intent of Study on the Use of a Dual Airborne Laser Scanner (ALS) in Conjunction with a Tactical Grade Inertial Measurement Unit (IMU) for Unmanned Aerial Vehicle (UAV) Navigation And Mapping in Unknown, Non-Global Positioning System (GPS), Environments"

5a. CONTRACT NUMBER
FA9550-05-1-0495

5b. GRANT NUMBER
FA9550-05-1-0495

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Uijt de Haag, Maarten

5d. PROJECT NUMBER
FA9550-05-1-0495

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Ohio University
105 Research & Technology
Center
Athens, OH 45701

8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific
Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The goal of our AFOSR proposal was to study the feasibility, characteristics and limitations of using two Airborne Laser Scanners (ALS) mounted on an Uninhabited Airborne Vehicle (UAV) to aid its Inertial Measurement Unit (IMU) in unknown terrain environments. One area of interest to AFRL is the ability to navigate in GPS-denied environments where prior information about the terrain the UAV is traversing, is unknown. Conventional TRN schemes are inadequate since they all require prior terrain information in the form of a terrain elevation database. Ohio University's proposed concept of using Dual Airborne Laser Scanner (Dual ALS) meets the requirement of not needing prior terrain information. Conceptually similar to an Inertial Navigator, Dual ALS is a dead-reckoning system that keeps track of a vehicle's position state changes over time, since initialization. The Dual ALS error states can then be used to correct or reset the IMU states, thus effectively constraining its drift error. Simulation results provided in this final report demonstrate that the concept works extremely well with residual horizontal drift errors of magnitudes as small as 60 meters per hour.

15. SUBJECT TERMS
Navigation, Airborne Laser Scanner, Terrain Referenced Navigation, Inertial Measurement Unit, Unknown Terrain Environments

16. SECURITY CLASSIFICATION OF: UNCLASSIFIED			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Zofia Starzyk
a. REPORT	b. ABSTRACT	c. THIS PAGE	UL	19	19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED			(740) 593-1512

This page has been intentionally left blank

Use of Dual Airborne Laser Scanner in Conjunction with a Tactical Grade Inertial Measurement Unit for Unmanned Aerial Vehicle Navigation and Mapping in Unknown, Non-Global Positioning System Environments

Ananth K. Vadlamani, Maarten Uijt de Haag, Frank van Graas

Ohio University Avionics Engineering Center

Jacob L. Campbell, Mikel M. Miller

AFRL/SNRN

Abstract

The goal of our AFOSR proposal was to study the feasibility, characteristics and limitations of using two Airborne Laser Scanners (ALS), mounted on an Uninhabited Airborne Vehicle (UAV) to aid its Inertial Measurement Unit (IMU) in unknown terrain environments. An IMU is at the heart of many modern navigation systems, but it has its drawbacks such as drift errors in its velocity and position estimates. The integration of Global Positioning System (GPS) measurements with the outputs of an IMU works exceptionally well in containing the IMU drift errors and provide continuous navigation solutions. However, GPS, not being a vehicle autonomous system is susceptible to intentional or un-intentional interference or signal blockages in urban areas. Even prior to GPS, a complementary navigation scheme known as Terrain Referenced Navigation (TRN) was used to constrain IMU errors. TRN has attracted renewed interest in the navigation field because of its robustness and improvement in sensors for terrain measurement. One area of interest to AFRL is the ability to navigate in GPS-denied environments where prior information about the terrain the UAV is traversing, is unknown. Conventional TRN schemes are inadequate since they all require prior terrain information in the form of a terrain elevation database. Ohio University's proposed concept of using Dual Airborne Laser Scanner (Dual ALS) meets the requirement of not needing prior terrain information. Conceptually similar to an Inertial Navigator, Dual ALS is a dead-reckoning system that keeps track of a vehicle's position state changes over time, since initialization. The Dual ALS error

states can then be used to correct or reset the IMU states, thus effectively constraining its drift error. Simulation results provided in this final report demonstrate that the concept works extremely well with residual horizontal drift errors of magnitudes as small as 60 meters per hour.

Keywords: Dual Airborne Laser Scanner, Dual ALS, Autonomous Navigation, non-GPS environments, unknown terrain environments.

I. INTRODUCTION

Inertial Navigation Systems (INS) are used in all modern flight control applications because of their ability to provide all necessary states of position, velocity and attitude at high update rates. INS works on the principle of dead-reckoning, wherein, it keeps track of the vehicle's accelerations and rotations. These sensed acceleration and rotation states are processed to yield the vehicle's attitude, velocity and position estimates. The limitation of an INS is that any errors present in the acceleration states get integrated and magnified and result in drift errors in velocity and position. Tactical grade IMUs can have position drift errors in the order of a few tens of nautical miles per hour, thus severely limiting their operational use. Proper calibration of an IMU's sensors can alleviate this problem but the process is often time-consuming and expensive. As the IMU market is experiencing a migration trend towards Micro Electro-Mechanical System (MEMS) sensors, drift errors in MEMS sensors are so much more an issue. An IMU has to be integrated with other techniques, sensors or systems that can limit its drift error, while preserving the IMU's advantages.

Schemes such as TRN have been used in the past to integrate with the IMU. TRN systems use prior knowledge of the terrain, in the form of terrain databases, and a terrain measurement sensor such as a radar or laser altimeter. A sensed terrain profile is created in-flight which is then compared with a set of probable flight profiles computed from the database. A matching algorithm selects the most probable flight profile and the IMU is updated with the TRN's best position estimate. TRN is a vehicle autonomous scheme whose only limitations are the required *a-priori* terrain database and error characteristics and resolution of the used databases. Two of the more famous TRN schemes that have been used in guided missiles and fighter aircrafts are TERrain COntour Matching (TERCOM) [1] and Sandia Inertial Terrain Aided Navigation (SITAN) [2][3].

In the 1990s, the complementary nature of GPS to an IMU was quickly realized and explored that gave rise to many integration schemes using a Kalman filter. An IMU has high update rates and low frequency errors, albeit poor accuracy; GPS on the other hand has good meter-level accuracy but high frequency noise and low update rates. Integration schemes using a complementary Kalman filter preserves all the better aspects of both systems such as high update rates, good accuracy and very little residual noise. In that aspect, GPS is the perfect counterpart to INS. However GPS has its drawbacks. GPS signals are vulnerable to interference, either intentional such as jamming or spoofing, or un-intentional such as from communication devices or other radio-frequency (RF) sources. In addition, a high dynamic mobile platform such as a UAV may need to fly in urban areas as part of its mission where GPS signal blockages from buildings give rise to a reduced constellation – a scenario known as “Urban Canyon”. There are other environments where a satellite navigation system is not available, such as the Moon or other extra-terrestrial exploration missions. In the context of our present research topic concerning UAV navigation, we simply assume that the UAV may have to fly through a GPS denied environment. In such a scenario, it is tempting to fall

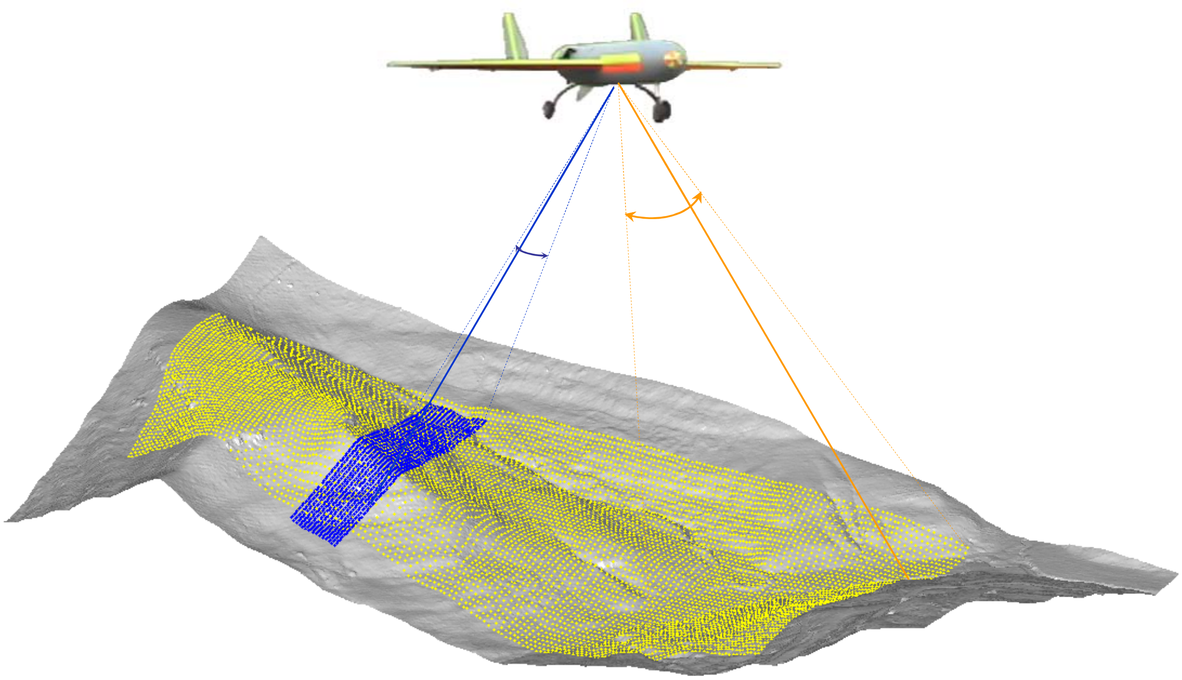


Figure 1. Dual ALS Concept Illustration

back on a TRN based integration scheme, except for one limitation: the UAV might have to fly into GPS-denied *and* an unknown terrain environment, while still being able to complete its mission.

Our solution to the lack of *a priori* terrain database information is simple: we create the map "on-the-fly". That is the reason for the Dual ALS setup. One ALS would ideally point a few degrees forward from nadir, creating a map of the terrain/features and a second ALS would point a few degrees rearward from nadir and used as a conventional TRN-like terrain measuring sensor. Both ALSs being similar in nature, it will be easier to quantify the error characteristics of the system. Our proposed concept is an enabling technology for a complete vehicle autonomous mapping and navigation system that neither requires GPS nor any other *a-priori* information.

II. NOMENCLATURE

Both the ALSs in the Dual ALS system have been named for their location on the vehicle as well as for their functionality. The forward pointing ALS will henceforth be referred to as the 'Fore ALS' or the 'Mapping ALS'. The ALS pointing rearward will henceforth be referred to as the 'Aft ALS' or the 'Navigation ALS'.

III. DUAL ALS INERTIAL AIDING ALGORITHM

A dead-reckoning algorithm has been developed that estimates the IMU position error states over every update interval. These estimated position error states are then subtracted from the IMU (erroneous) position states to yield corrected position states. A more complex algorithm involving other state variables is under investigation. A system block diagram is shown in Figure 2 and a description of the algorithm has been provided in the following sections.

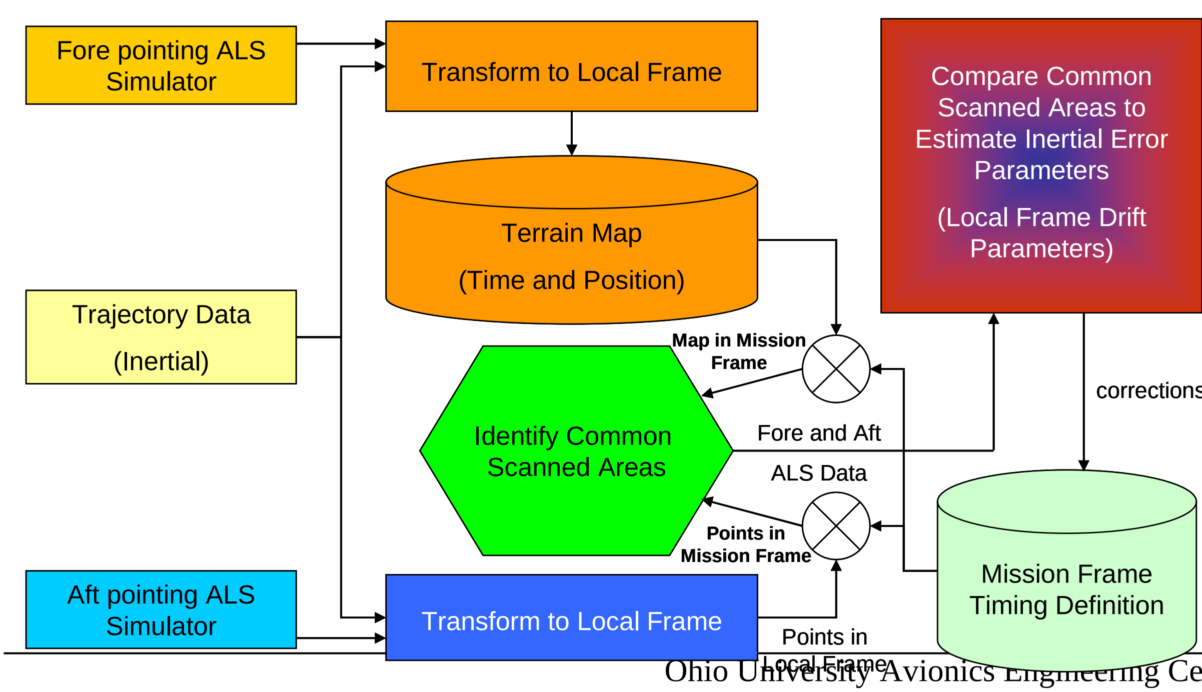


Figure 2. Dual ALS System Block Diagram

Considering a UAV platform and associated computer memory constraints, the terrain map generation aspect of the Dual ALS algorithm has been designed to only hold enough terrain map data as to provide valid data to the navigation scheme; beyond that, the data is overwritten. The number of seconds of valid terrain data that will be held in computer memory will depend on the vehicle's velocity and the angular spacing between the fore and aft

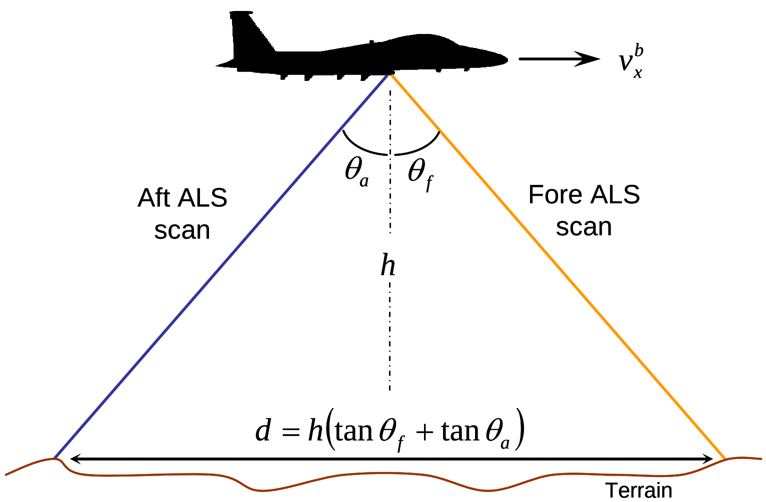


Figure 3. Distance between Fore and Aft ALS scans

ALS pointing angles.

The time between scans is given by:

$$\Delta t_{fa} = t_{fore} - t_{aft} = \frac{h(\tan\theta_f + \tan\theta_a)}{v_x^b} \tag{1}$$

Where,

Δt_{fa} is the time between aft and fore ALS scans (to scan the same terrain patch),

h is the height of the aircraft,

θ_f, θ_a are the forward and rearward pointing angles of the fore and aft ALS respectively and

v_x^b is the velocity of the aircraft expressed in its body frame.

A plot of Δt_{fa} as a function of aircraft height for different ALS pointing angles is shown in Figure 4.

In swarming applications, wherein the first UAV's terrain map has to be used by other following vehicles, the memory requirements of the terrain map are different and mainly mission-specific. For optimal algorithmic

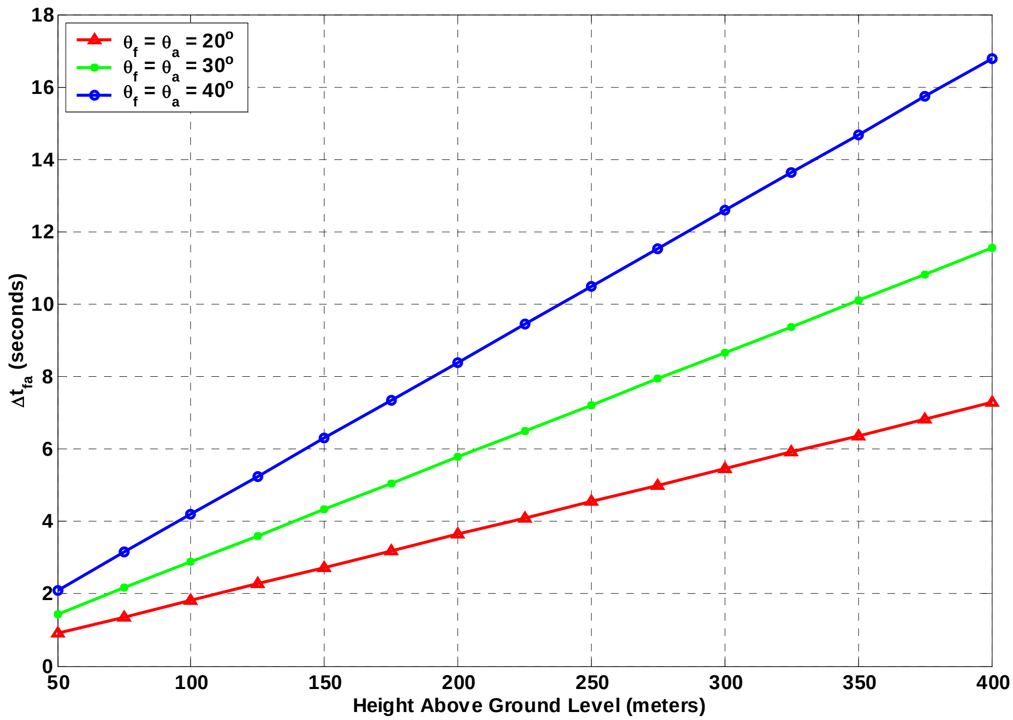


Figure 4. Time between Scans for Aircraft Velocity of 40 m/s

performance, each ALS measurement (pulse) has to be time-tagged with respect to an absolute or mission-specific time frame. The importance of proper timing on the accuracy of the system cannot be overemphasized!

There are three main aspects to the Dual ALS algorithm: ALS footprint co-ordinate computation, a relative navigation scheme and a timing scheme.

III.i. ALS Footprint Co-ordinate Computation:

Since even the high update rates of an IMU lower than the higher pulse repetition rate (PRR) or pulse repetition frequency (PRF) of the ALS, the aircraft positions and attitudes derived from the IMU are interpolated (using suitable techniques) to obtain a valid reference position for each of the ALS pulses. By considering the range and angle measurement of an ALS pulse and the unit pointing angle, a three-tuple vector of the pulse footprint coordinates is computed in the ALS frame. Considering any lever-arm and orientation offsets that may exist with respect to the IMU, the footprint co-ordinate vector is transformed into the IMU body frame using vector addition and direction cosine matrices (DCM) [4]. Finally, geo-referencing of the ALS footprints is performed by expressing the position vector in the Earth-Centered-Earth-Fixed (ECEF) frame. The presented analysis was performed in the Universal Transverse Mercator (UTM) projection coordinates. One may choose to express the ALS footprint

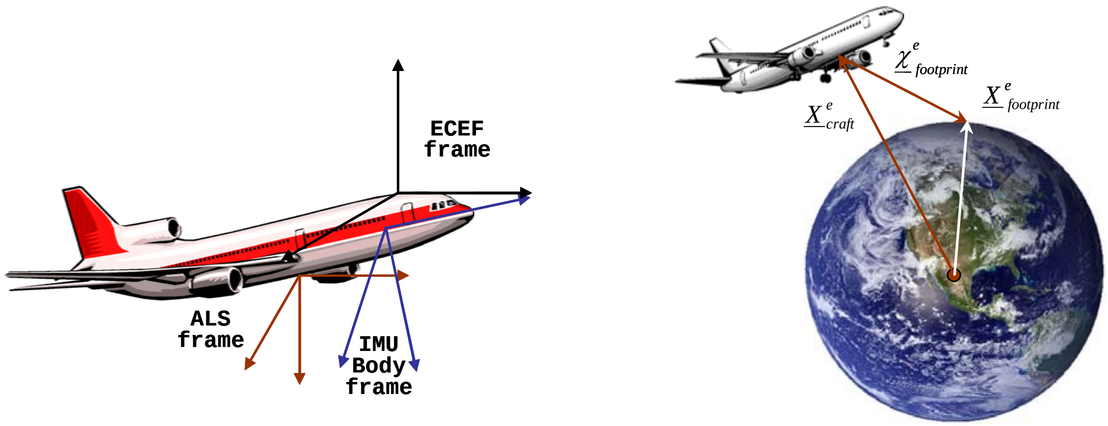


Figure 5. Geo-referencing of ALS Measurements

coordinates in any convenient frame, as long as the frame definitions stay consistent. The footprint geo-referencing scheme is illustrated here.

The ALS pulse footprint coordinates in the ECEF frame are computed as:

$$\underline{X}^{e}_{footprint} = \underline{X}^{e}_{craft} + C_n^e C_b^n C_{ALS}^b \, \underline{\chi}^{ALS}_{footprint} \tag{2}$$

Where,

$\underline{X}^{e}_{footprint}$ is the ALS pulse footprint position vector in the ECEF frame,

$\underline{X}^{e}_{craft}$ is the aircraft (ALS unit specifically) position vector in ECEF frame,

$\underline{\chi}^{ALS}_{footprint}$ is the ALS pulse footprint position vector in the ALS frame,

C_p^q is the notation denoting a DCM that transforms a vector from the p-frame to the q-frame.

In equation (2), the sub- and superscripts named ‘b’ denote the IMU frame or aircraft body frame, ‘n’ denotes the navigation frame (North, East, Down) as computed by the IMU and ‘e’ denotes the ECEF frame. After geo-referencing the terrain map coordinates as well as the navigation ALS footprint coordinates, they were converted to UTM easting, northing and height (above mean sea level (MSL)) coordinates.

III.ii. Relative Navigation Scheme:

As the name suggests, this is a navigation algorithm similar to a conventional TRN system that conducts a three-dimensional search, (x, y, z) in position search space. The position offsets resulting in a maximum cost-function (maximum or minimum value of the appropriate comparison metric) are the best candidate error states of the aircraft position relative to the fore ALS generated terrain map. There are two main aspects to the navigation scheme: a) Identification of a common terrain patch illuminated by both ALS, performed by Delaunay triangulation, b) 3-D offset search by looking for the best agreement of height profiles.

III.ii.a) Delaunay Triangulation: Although the map generated by fore ALS serves as our reference terrain database, it lacks one useful feature of a regular post-processed digital terrain elevation model (DTEM): Uniform Grid Spacing. The fore ALS terrain map is in the form of a point cloud, unevenly spaced and possibly containing measurement 'holes'. A 2-D Delaunay triangulation scheme is used for identification of the vertices of the smallest triangle enclosing the requested point. The requested points are the navigation ALS footprints. All the points that fall outside the terrain map limits do not have an enclosing triangle and are thus ignored. The height at each of the horizontal coordinates (of valid navigation ALS footprints) is interpolated using the vertex heights of the corresponding Delaunay triangles (formed from the terrain map). An illustration of the terrain map, the aft ALS

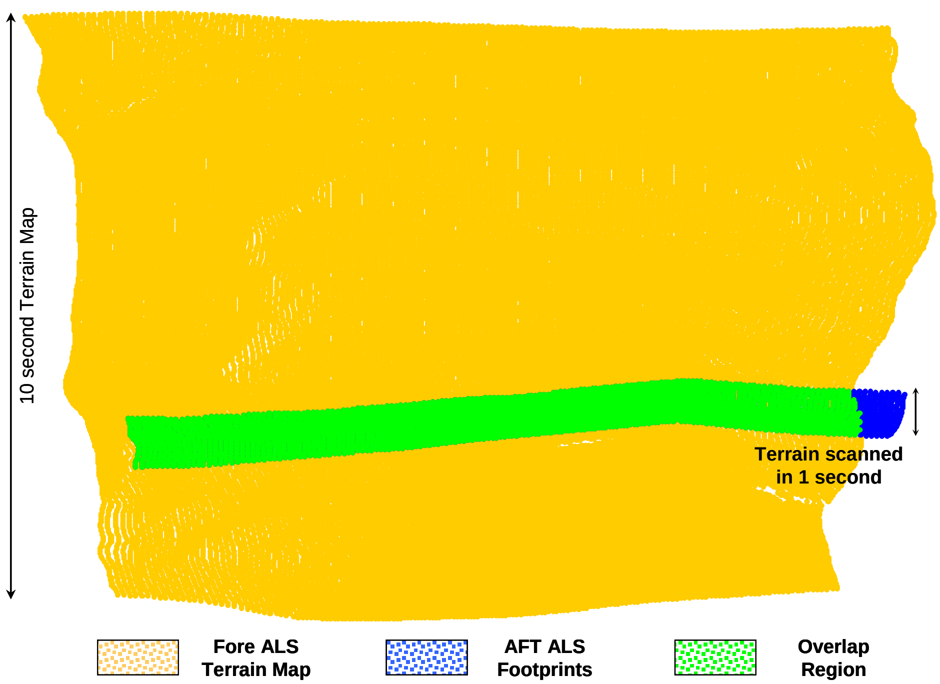


Figure 6. Identification of Overlap Region from both ALS Scans

points and the common overlap area is shown in Figure 6.

III.ii.b) Three-Dimensional Offset Search: The next step in the computation of the relative navigation solution is the three-dimensional search for a 3-D offset in position. The two height profiles; one computed during geo-referencing the aft ALS footprints and the other from the terrain map lookup, are compared for best agreement using a suitable comparison metric over a horizontal search grid. There are a few different comparison metrics that may be used, some of which are summarized in Table 1.

TABLE 1 – COMPARISON METRICS FOR TERRAIN HEIGHT PROFILES

Metric	Formula
Sum of Absolute Error (SAE)	$\sum_{i=1}^{N} \left| h_i - {}_{map}h_i \right|$
Sum of Squared Error (SSE)	$\sum_{i=1}^{N} \left(h_i - {}_{map}h_i \right)^2$
Mean Squared Error (MSE)	$\frac{1}{N} \sum_{i=1}^{N} \left(h_i - {}_{map}h_i \right)^2$
Chi-squared Statistic	$\frac{1}{\sigma^2} \sum_{i=1}^{N} \left(h_i - {}_{map}h_i \right)^2$
Covariance (at zero lag) Cross-correlation is similar but without subtracting the mean values	$C\left(h, {}_{map}h\right) = \frac{1}{(2N+1)} \sum_{i=1}^{N} \left(h_i - \bar{h}\right)\left({}_{map}h_i - {}_{map}\bar{h}\right)$
Correlation Coefficient	$\frac{C\left(h, {}_{map}h\right)}{\sqrt{C(h,h)C\left({}_{map}h, {}_{map}h\right)}}$, varies between -1 and 1

The computational complexity of the metrics increases from the top to bottom of the table. For this reason, SAE and SSE are preferred. However, when dealing with data whose length may not be constant, a normalized metric such as MSE may be more appropriate. A sample plot showing the MSE surface over a 10m x 10m square grid is shown in Figure 7.

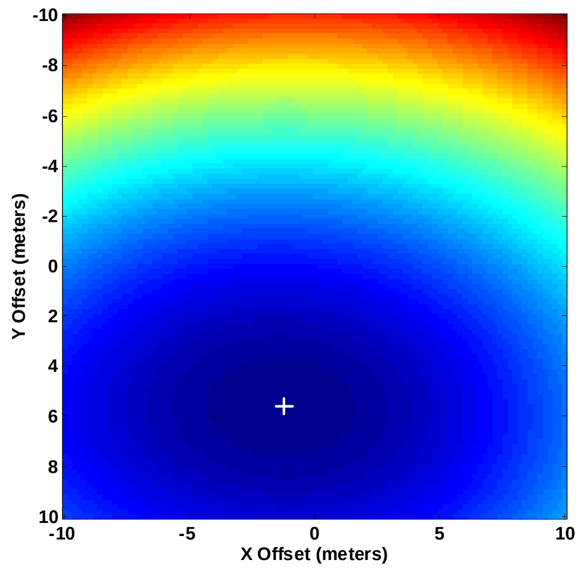


Figure 7. Mean Squared Error Surface and its Minimum Value

Since the MSE surface is smooth with a unique local minimum within a small search space, a gradient search technique as described in [5] may be used to improve convergence times. In order to save computation time, the height offset can be computed as the difference of means (as in 'average') of the two height profiles at the minimum MSE x and y offset locations. Note that we need to look for a maximum instead of a minimum when using the cross-correlation or correlation coefficient metrics.

III.iii. Timing Scheme:

Accurate timing is essential to the success of a dead-reckoning scheme such as the Dual ALS. The time between scans as a function of h_{AGL} at constant velocity was shown in Figure 4. However, aircraft velocity is never constant, not to the accuracies required anyway. Figure 8 shows the time between overlap of ALS scans as a function of velocity for fixed h_{AGL} of 1000 ft. The timing scheme keeps track of aircraft velocity between (algorithm) updates from the computed 3-D position offsets and measured time between both ALS scans.

$$\underline{v} = \underline{\Delta x}_{mn} / \Delta t_{mn} \tag{3}$$

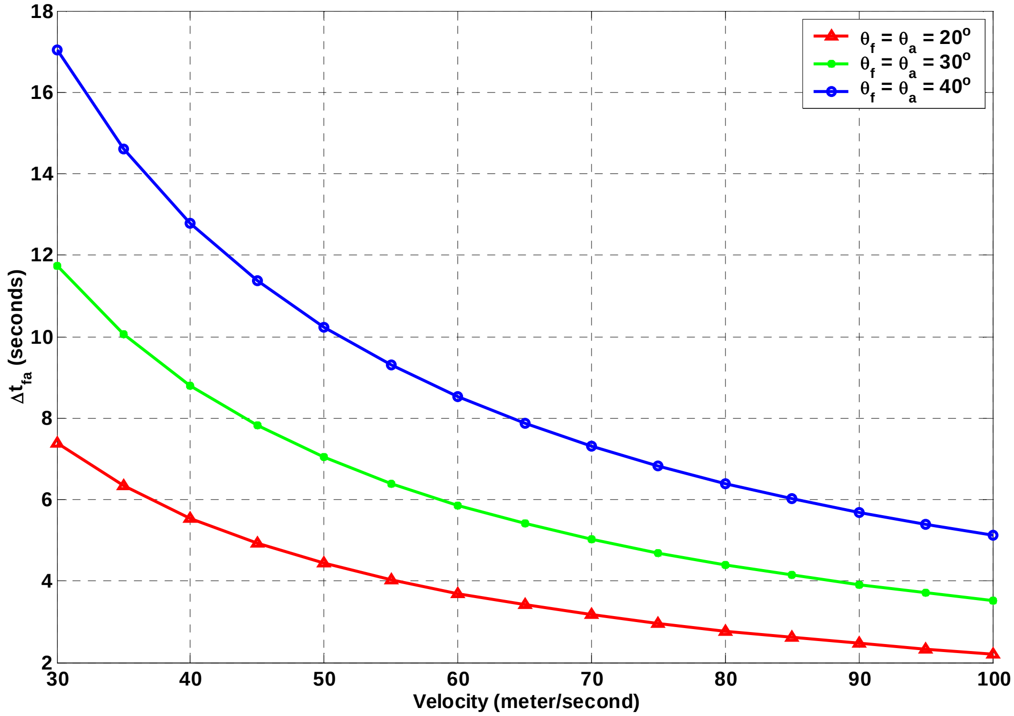


Figure 8. Time between Scans as a function of Velocity for 1000 ft AGL

Where,

$\underline{v}$ is the velocity vector,

$\underline{\Delta x}_{mn}$ is the offset vector of the navigation footprints with respect to the map,

Δt_{mn} is the time between the fore ALS (map) and aft ALS (navigation) scans ($\Delta t_{mn} = t_n - t_m$).

Acceleration effects are neglected in this analysis. The updated position is computed using the kinematics equation:

$$\underline{X}_{r+1} = \underline{X}_r + \underline{v}\Delta t_{rn} \tag{4}$$

Where,

$\underline{X}_{r+1}$ is the updated reference position vector,

$\underline{X}_r$ is the last known best reference position vector,

Δt_{rn} is the time elapsed since the last position update ($\Delta t_{rn} = t_n - t_r$).

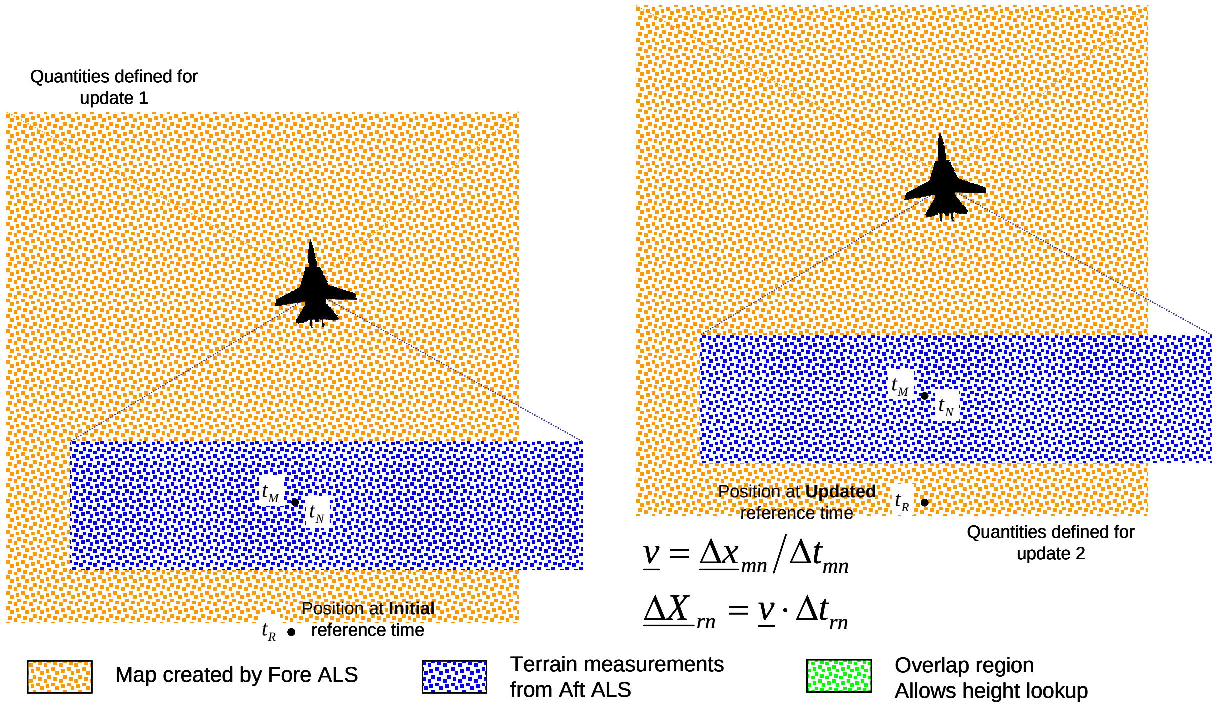


Figure 9. Dual ALS Update Concept

IV. DUAL ALS SIMULATION

Software for the Dual ALS algorithm was written in MATLAB™ and C programming languages using inertial sensor data and aircraft truth trajectories collected during actual flight tests. The Ohio University Avionics Engineering Center conducted flight tests in Braxton, WV on December 12th 2004 and January 14th 2005 to demonstrate real-time ALS based precision approach capability in a known environement [5]. The Center's DC-3 flying laboratory was configured to collect inertial data from a Honeywell HG1150 – a navigation grade inertial navigator, position and high accuracy carrier phase measurements from a NovAtel OEM4 GPS receiver. The GPS measurements were post-processed to from a Kinematic GPS (KGPS) truth trajectory. Aircraft attitude as provided by the HG1150 IMU was treated as the true attitude. An ALS simulator has been developed at Ohio University that uses this truth trajectory and attitude data, in conjunction with a high resolution terrain database to generate ALS range measurements [6]. The ALS simulator block diagram is shown in Figure 10.

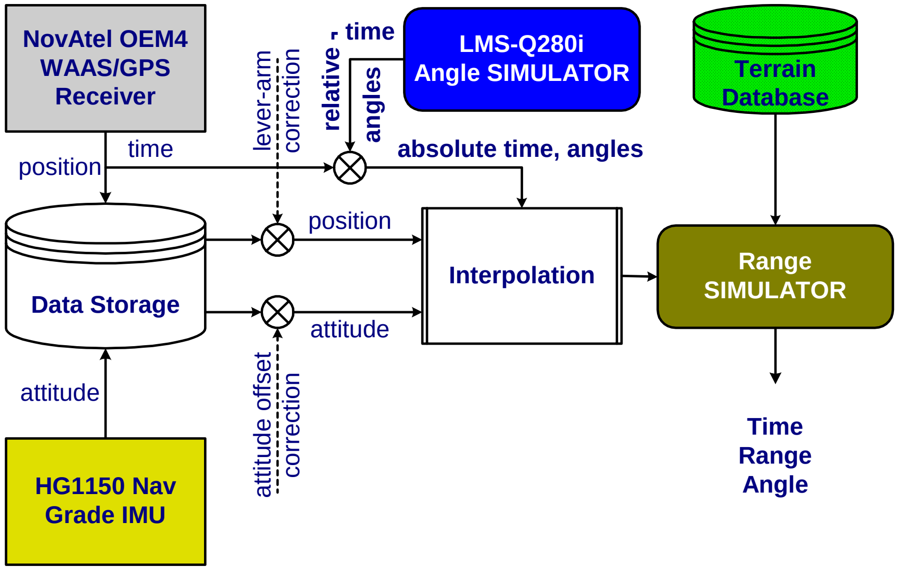


Figure 10. ALS Simulator Block Diagram

Ohio University has acquired a medium-range 2-D ALS scanner from RIEGL® Laser Measurement Systems, the LMS Q-280i with a grant from the Defense University Research Instrumentation Program (DURIP) [7]. The timing and angle characteristics of the LMS-Q280i were simulated to form the block labeled 'Angle Simulator' in Figure 10. A high resolution LIDAR terrain database provided by West Virginia GIS Technical Center was used to generate ALS range measurements by a ray-tracing algorithm; labeled 'Range Simulator' in Figure 10. Plots of the Angle simulator output/timing characteristics and the Range simulator accuracy (compared with the terrain database) are provided in Figures 11a and 11b, respectively.

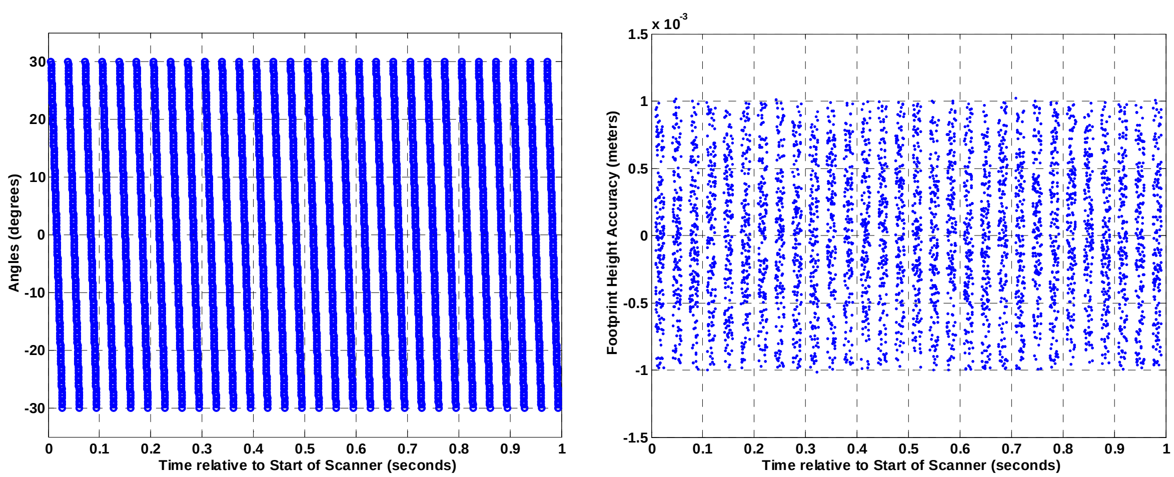
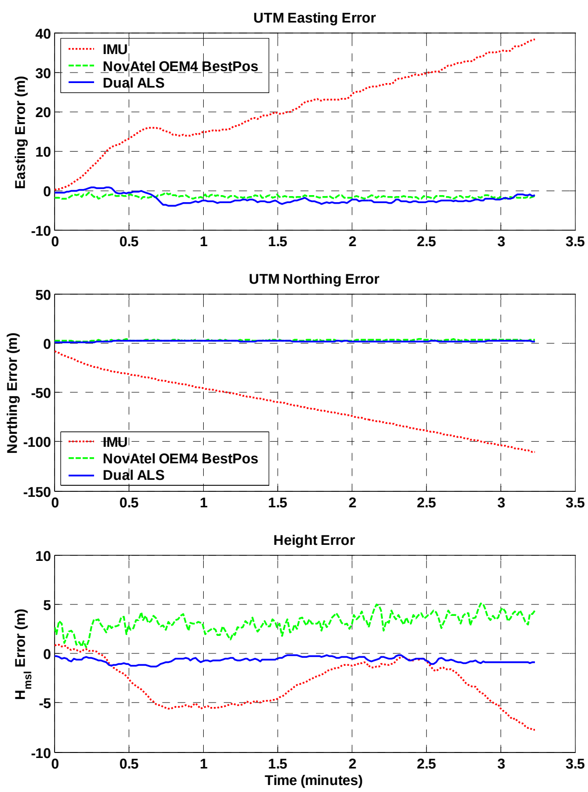


Figure 11a. Angle Simulator Output; 11b. Range Simulator Accuracy

V. RESULTS

The results of the Dual ALS simulation and algorithm performed on the eight approach trajectories of the January 14th 2005 flight test are plotted in this section. The sample plot of Figure 12a shows the position error in UTM easting, northing coordinates as well as height (MSL) error for the HG1150 IMU, NovAtel OEM4 'BestPos' log and for the Dual ALS algorithm. The IMU drifts are clearly observed. The errors in 'BestPos' and Dual ALS are of the same order with a lot less noise on Dual ALS. A more insightful plot is that of Figure 12b that shows a comparison of the total Horizontal error in all three sensors/methods.



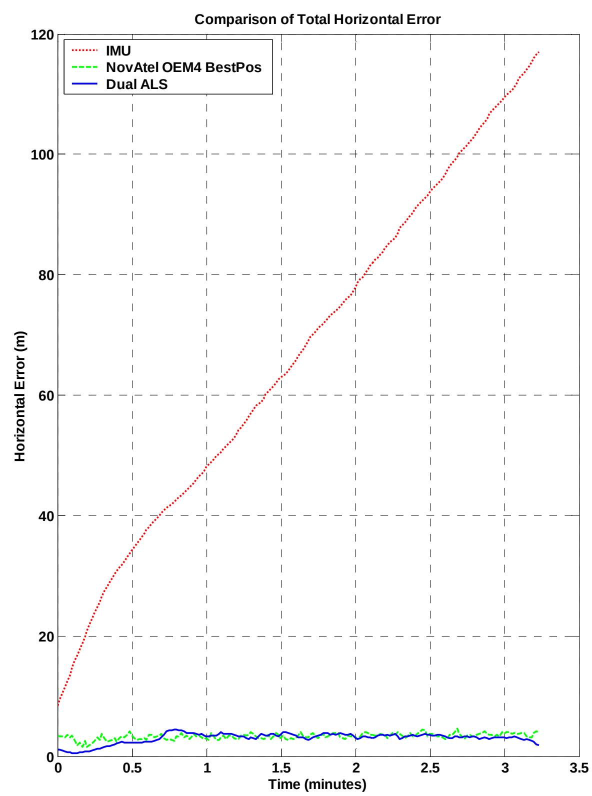
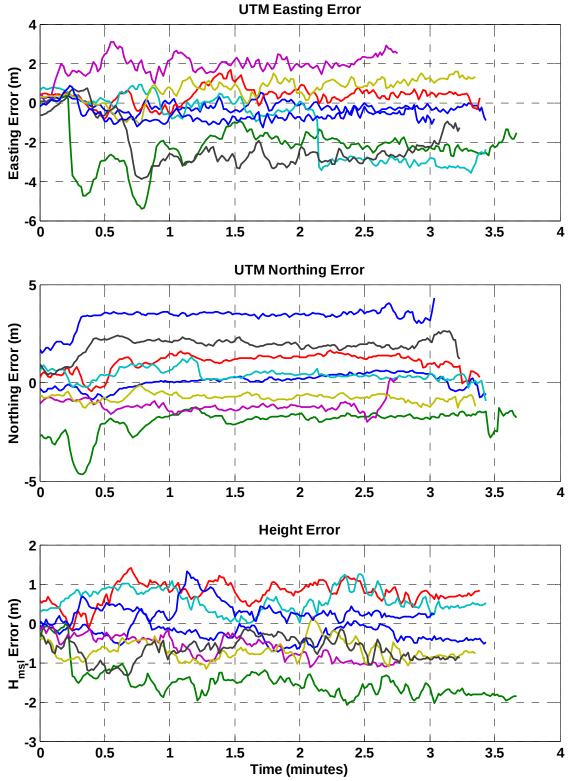


Figure 12a. Comparison of UTM Easting, Northing and Height Error
Figure 12b. Comparison of Total Horizontal Error

The error characteristics from the Dual ALS algorithm are expected to be a random walk process, since the error growth depends upon the accuracy of the position search technique at every update. Assuming the position search accuracy is ≈ 2 meters of standard deviation [5], the standard deviation of Dual ALS algorithm is expected to be $2\sqrt{t}$, where '*t*' is time in seconds. So over four minutes, $\sigma_{DualALS} = 2\sqrt{240} \approx 31$ meters. The simulation results have shown a much better error performance and their statistics need further analysis.



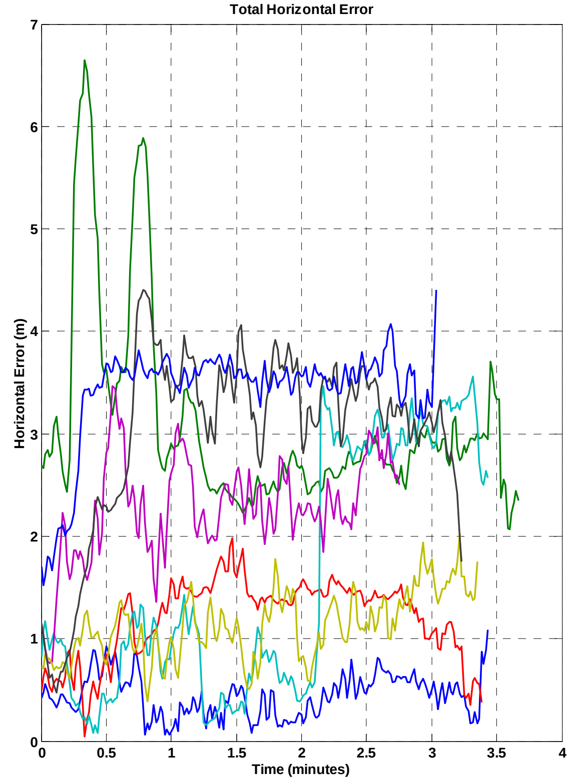


Figure 13a. Easting, Northing and Height Error for 8 Test-Flight Simulations
Figure 13b. Total Horizontal Error for 8 Test-Flight Simulations

A plot of the ensemble mean and standard deviation as a function of time is shown below.

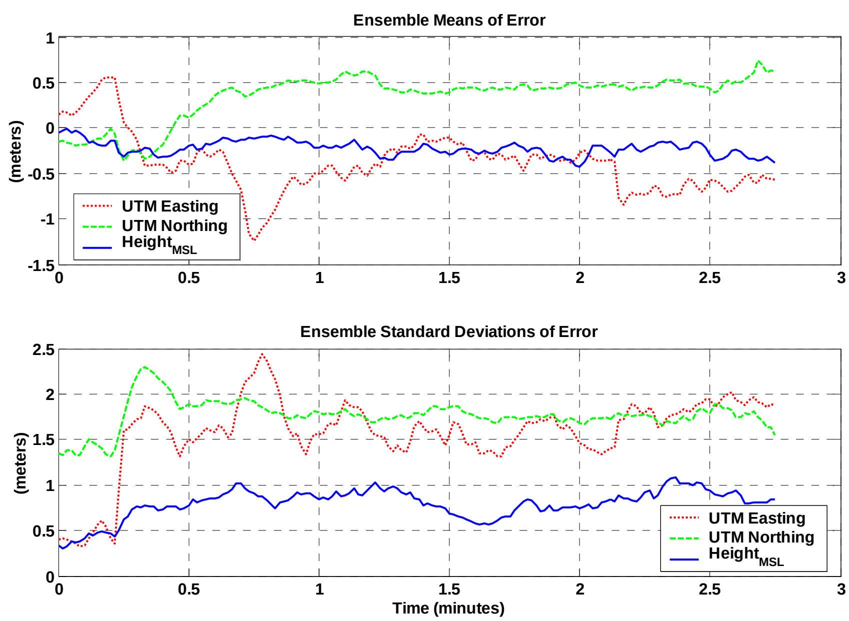


Figure 14. Ensemble Mean and Standard Deviation of Error Process

VI. OTHER ENVISIONED APPLICATIONS

The system concept and algorithm as applied to Dual ALS has the potential for immense possibilities for:

<u>UAV fleet</u>: One UAV equipped with two ALS and a tactical grade IMU could act as a scout ship to map out unknown territories; correcting its map with the computed IMU error correction terms. The scout UAV could then transmit the map via a telemetry/communications link to a fleet which could then navigate based on the received map, their on-board (one) ALS and a tactical grade or even MEMS IMU. It is expected that in the future, improvement in the quality and stability of MEMS sensors, reduction in the weight and price of optical/laser sensors will make it possible to equip even small, model-aircraft sized UAVs with these sensors.

<u>Real-Time Cartography</u>: Using smart integration schemes and pre-surveyed lever-arm and orientation offsets between sensors, real-time maps could be produced for applications such as reconnaissance, hazard management, feature and obstacle databases, city models, etc.

<u>Lunar and Planetary Exploration</u>: The space-grade IMU aboard the exploration vehicle could be calibrated using stellar sightings prior to entering the moon's or other planet's atmosphere and then use the mapping and navigation capabilities of the Dual ALS concept. The landscapes being devoid of trees or man-made objects would eliminate the need for processes such as vegetation extraction and building/feature separation, being truly a 'bare-planet' approximation.

<u>Motion or Change Detection</u>: ALS are capable of mapping with very high point density. Using feature identification and segregation techniques, the map points can be classified as representing either terrain or features/objects such as buildings, trees or moving vehicles. The aft ALS points can be classified similarly and the navigation update computed purely based on the points representing terrain. The feature points from both ALS scans can then be matched to detect motion and estimate the velocities of mobile vehicles.

VII. FUTURE WORK

The algorithm will be expanded to include other error state variables such as velocity and acceleration and their impact to the accuracy of the system will be investigated. Using feature extraction techniques, this concept of navigation can be performed purely based on the features instead of terrain. The high spectral content of features permits a unique position solution to be computed corresponding to the unique (global) minimum in the search space. A blended solution using a Kalman filter is the next logical step in order to minimize the cumulative effects of a false position fix. 3-D imaging lasers, also known as 'Flash LIDARS' are currently under development. It will be advantageous to use just one such Flash LIDAR to perform the navigation scheme presented here. An added advantage is the elimination of the need to time-tag every pulse, since with a Flash LIDAR, an entire image frame can be referenced to a single time instant, thus simplifying the timing scheme.

VIII. CONCLUSIONS

An inertial navigator aiding concept incorporating two ALS units with a dead-reckoning algorithm has been demonstrated to effectively constrain the inertial navigator's position error growth. This Dual ALS algorithm was found to improve the position error drift performance to better than a meter per minute and thus by linear projection, probably better than 60 meters per hour. The algorithm was analyzed using a combination of real flight-test data and simulated data. The ALS measurements were simulated using inertial and GPS data from flight tests and a high resolution terrain database. The Dual ALS inertial aiding concept, once mature and implemented using the recommendations listed in the 'future work' section, could become a complete vehicle autonomous mapping and navigation system:– a backup to GPS.

REFERENCES

[1] Baird, C. A., M. R. Abramson, "A Comparison of Several Digital Map-Aided Navigation Techniques", *Proceedings of the IEEE PLANS*, pp. 286-293, 1984.

[2] Hostetler, L. D., R. D. Andreas, "Nonlinear Kalman Filtering Techniques for Terrain-Aided Navigation", *IEEE Transactions on Automatic Control*, Vol. AC-28, No. 3, March 1983.

[3] Boozer, D. D., M. K. Lau, J. R. Fellerhoff, "The AFTI/F16 Terrain-Aided Navigation System", Proceedings of the IEEE National Aerospace and Electronics Conference, NAECON, pp. 351-357, 1985.

[4] Titterton, D. H., J. L. Weston, "Strapdown Inertial Navigation Technology", Peter Peregrinus Ltd., 1997, Ch. 3.

[5] Campbell, J. L., M. Uijt de Haag, F. van Graas, "Terrain Referenced Precision Approach Guidance", Proceeding of the ION National Technical Meeting, San Diego, CA., 2005.

[6] Vadlamani, A., M. Smearcheck, M. Uijt de Haag, "Preliminary Design and Analysis of a LIDAR based Obstacle Detection System", Proceedings of the 24th Digital Avionics Systems Conference (DASC), Washington D. C., 2005.

[7] Campbell, J., M. Uijt de Haag, F. van Graas, "Ohio University DURIP Award – Summary Report", Ohio University Technical Report, April 2004.